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Effective wall slip in Couette and parallel plates flow of drag-reducing surfactant solutions

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Abstract

This paper presents experimental results of the study on the rheological properties of drag-reducing surfactant solutions. It is the main objective of the present work to establish the possibility of wall slip corrections for Couette and parallel plates rheometers. In addition, methodology of samples preparation of aqueous surfactant solutions to rheological measurements is presented. In the study the cationic surfactant cethyltrimethylammonium chloride (CTAC) was used. The additive enhancing micellar association was sodium salicylate (NaSal). In solutions used the molar ratio ζ of CTAC to NaSal was in the range from 1 to 2. Concentrations of the solutions were equal to 1000 and 6000 ppm. Experimental data presented show that during the flow curve measurements for surfactant solutions there is a possibility of occurrence an effective wall slip. Correcting measurement results by the use of simple methods does not provide guaranties to obtain real flow curve characteristics. Best solution seems to be in using the measuring systems with rough surfaces..

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Keywords: Effective wall slip; surfactant solutions

1. Introduction

An addition of small amounts of surfactants to water can result in drag reduction of turbulent flows. The common feature of drag-reducing surfactants is the ability to generate in a solution the spatial

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microstructure built of long micelle associates, known as worm or threadlike ones. Dilute surfactant solutions are very sensitive to shearing. Shear can induce structural transformations in the solution. As a result, macroscopic properties of the solution depend on the shear rate of the system. Many micellar surfactant solutions exhibit the complex rheological properties such as SIS (shear-induced structure), viscoelasticity and high extensional viscosity/shear viscosity ratios [2].

Drappier et al. [3] suggest that the shear-induced phase induces the effective wall slip in flows of surfactant solutions. This effective wall slip in turn, is due to the formation of a shear-induced gel (shear induced structure) that can break in the near-wall region. Shear-induced gelation in dilute solutions of wormlike micelles followed by a fracture of the gel that can lead to an effective (apparent) wall slip has been observed also in previous papers (for example [3-9]).

This paper presents experimental results of the study on the rheological properties of drag-reducing surfactant solutions. It is the main objective of the present work to establish the possibility of wall slip corrections for Couette and parallel plates rheometers. In addition, methodology of samples preparation of aqueous surfactant solutions to rheological measurements is presented.

Nomenclature

$C_{p,s}$	concentration of CTAC
R	radius
R_i	bob radius
R_o	cup radius
$u_s(\tau^*)$	slip velocity at the cup or bob surface
Ω	angular velocity
$\dot{\gamma}$	shear rate
$\dot{\gamma}_a$	apparent shear rate
η	viscosity
η_a	apparent viscosity
κ	is the cup/bob ratio = R_i/R_o
ζ	molar ratio of CTAC to NaSal

2. Experimental set-up

2.1. Rheological measurements

All rheological measurements were performed using rotational stress rheometer Physica MCR 501 (Anton Paar) with concentric cylinder measuring geometry with 3 different cap and bob diameters and parallel plates. Both smooth and rough plates were used to study the wall slip behavior. The depth of the groves in the rough plates was 45 μm.

2.2. Materials

In the study the cationic surfactant cethyltrimethylammonium chloride (CTAC) was used. The additive enhancing micellar association was sodium salicylate (NaSal). In solutions used in the study the molar ratio ζ of CTAC to NaSal was in the range from 1 to 2. The solutions used contained the surfactant in the concentrations of 1000 and 6000 ppm. The solvent was the distilled water. Measurements were performed at 20 ^{o}C.

Preliminary studies showed that the results of rheological measurements for the solutions of CTAC/NaSal strongly depend on the method of sample preparation. Fig. 1 shows the flow curves for two samples of the same solution at a concentration of 1000 ppm. The measurement results differ qualitatively and quantitatively. This solution was prepared by slow adding a solution of NaSal to solution of CTAC at 60°C. The CTAC/NaSal system was mechanically mixed during preparation. This procedure did not allow to obtain a homogeneous solution. Therefore, the solution was heated to temperature 90°C and maintained at this temperature for 30 minutes. Then it was mixed in a mechanical homogenizer at 20 minutes. An additional procedure for homogenization of the sample made it possible to obtain reproducible results.

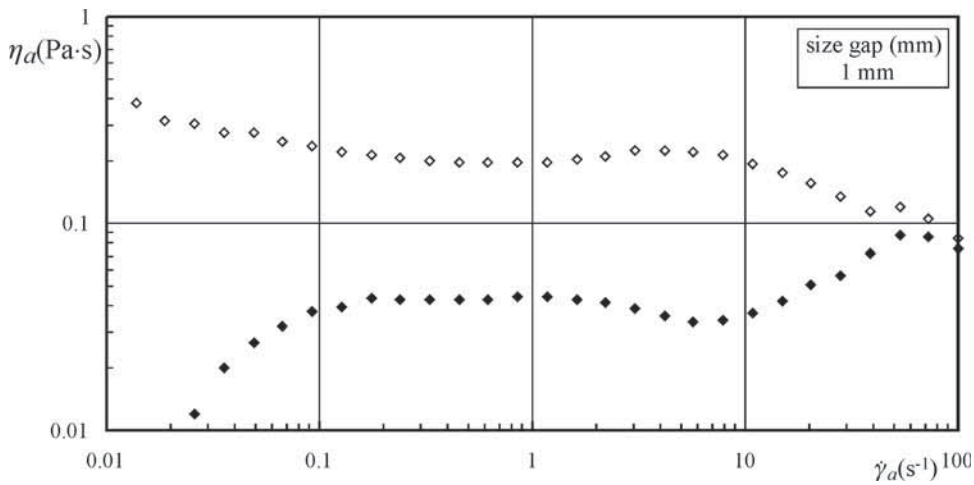

Fig. 1. Comparison of viscosity curves for the two samples of the same solution

3. Wall slip effect

3.1. Concentric cylinders

Figure 2 shows the viscosity curves for a solution of CTAC/NaSal with a concentration of 1000 ppm and a molar ratio of components $\zeta = 1$ made in the system of coaxial cylinder. It is evident that in the range of shear rate from 1 to 5 s^{-1} the viscosity of the solution apparently increases with increase of the measuring gap. It may indicate the occurrence of effective (apparent) wall-slip. At higher shear rates the course of experimental points is irregular, that is associated with the occurrence of unstable flow range. The obtained viscosity curves are characteristic for the solutions of surfactants, where long worm-like micelles are formed.

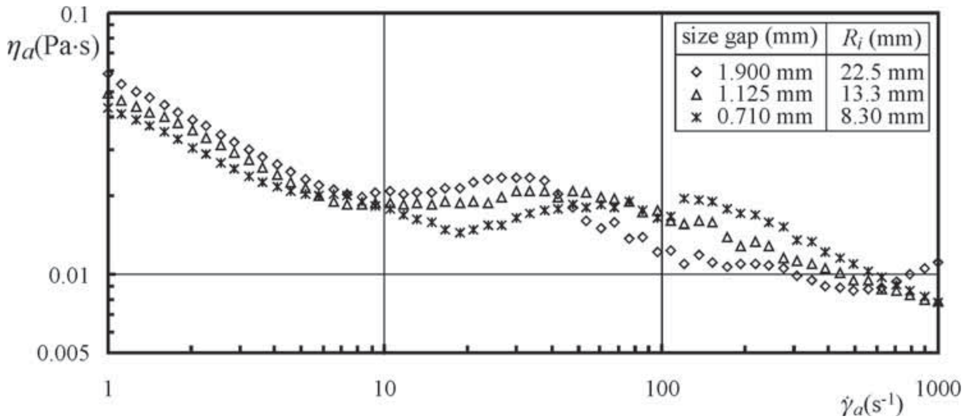

Fig. 2. Apparent shear viscosity versus apparent shear rate for a 1000 ppm CTAC/NaSal surfactant solution at gaps of 1.9; 1.125 and 0.710 mm in the concentric cylinders geometry at 20^{o}C

Figure 3 shows the viscosity curves corrected by using the method of Yoshimura and Prud'homme [1]. According to this method the effective slip velocity can be determined by making measurements with two different radii bobs, R_{i1} and R_{i2}, with cups sized to give the same κ.

$$u_s(\tau^*) = \frac{\kappa}{\kappa+1}\left[\frac{\Omega_1 - \Omega_2}{\dfrac{1}{R_{i1}} - \dfrac{1}{R_{i2}}}\right] \tag{1}$$

where $u_s(\tau^*)$ is the slip velocity at the cup or bob surface, κ is the cup/bob ratio = R_i/R_o, Ω – is the angular velocity, R_i – is the bob radius, R_o – is the cup radius.

In measurements three sets of concentric cylinders of different size gap were used. Correction of flow curves was performed for two pairs of coaxial cylinders: R_{i1}/R_{i2} = 13.3/22.5 mm and R_{i1}/R_{i2} = 8.3/22.5 mm. The cup/bob ratio was κ = 1.084. For both systems used of corrected viscosity curves overlap (Fig. 3).

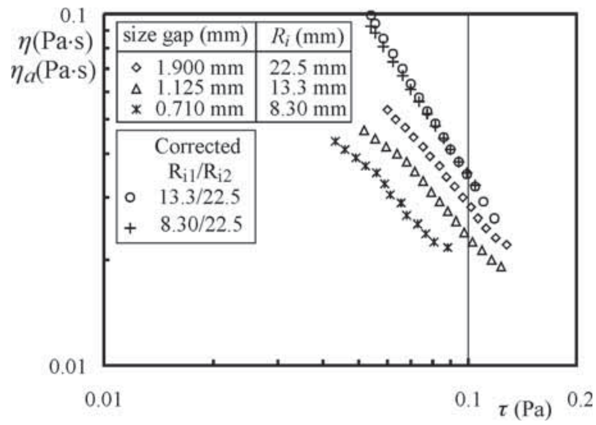

Fig. 3. Corrected shear viscosity versus shear stress for 1000 ppm ($\zeta = 2$) CTAC/NaSal solution

a)
b)

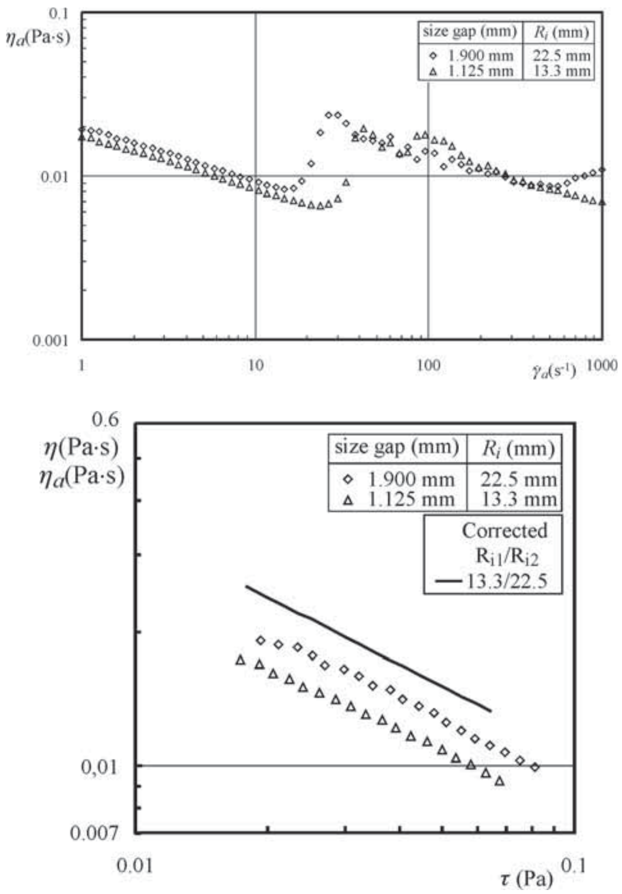

Fig. 4. Apparent shear viscosity vs. apparent shear rate (a) and corrected viscosity vs. shear stress (b) for 1000 ppm ($\zeta = 1$) CTAC/NaSal solution

In Figure 4 the flow curves for a solution with a concentration of 1000 ppm ($\zeta = 1$) has been presented. Comparing the viscosity curves in Figs 2 and 4 it can be seen that for solutions with a concentration of 1000 ppm (ζ = 1) there is a marked increase in viscosity above a certain value of shear rate associated with the formation of shear-induced state (SIS). Also for these solutions the courses of the plot $\eta = f(\dot{\gamma})$ can point to an effective wall-slip at low shear rates (below about 12 s^{-1}). However, in this case the difference between the viscosity curves obtained using cylinders of different size gaps was smaller than for the solution with a concentration of 1000 ppm and $\zeta = 2$. Strong apparent wall-slip effect occurs in the range of the formation of SIS. From direct measurements of the velocity profile, Hu et al. [5-7] also observed an apparent wall-slip near one or both walls in the Couette flow cell above the critical stress for shear thickening. In this range the method of Yoshimura and Prud'homme [1] proved to be impossible to apply, because the corrected viscosity values have taken a negative value.

3.2. Parallel plates

For solutions with a concentration of CTAC 500 and 1000 ppm, the studies have not been done in plate-plate system because these fluids have a high mobility. Therefore, in this system, measurements were performed for CTAC solution with a concentration of 6000 ppm and ζ = 2. Experiments were conducted using parallel plates of 50 mm diameter. For comparison also the parallel plates system with a rough wall were used. Flow curves for a solution with a concentration of 6000 ppm are shown in Fig. 4. The viscosity curve obtained for 0.75 mm gap is well below the curve obtained for a gap of 1 mm. Also in this case the appliance of the correction method of flow curves proposed by Yoshimura and Prud'homme [1] has failed. Figure 5 shows also the results of tests performed using parallel plate system with rough surfaces. The flow curves obtained by this method are well above the curves obtained using plates with smooth surface.

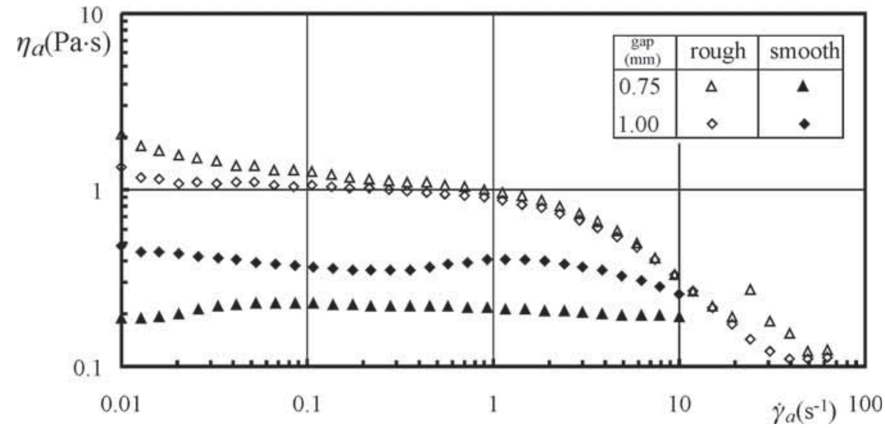

Fig. 5. Comparison of viscosity curves obtained in the system of parallel plates with a smooth and rough surfaces ($C_{p,s}$ = 6000 ppm, $\zeta = 1$)

In addition, the viscosity measured using gaps 0.75 and 1 mm have similar values. The results for the parallel plate systems with rough and smooth surfaces indicate that in the flow of CTAC/NaSal solution with a concentration of 6000 ppm effective wall slip is present.

4. Conclusions

Experimental data presented in this work show that during the flow curve measurements for surfactant solutions there is a possibility of occurrence an effective wall slip. Correcting measurement results by the use of simple methods does not provide guaranties to obtain real flow curve characteristics. Best solution seems to be in using the measuring systems with rough surfaces.

Acknowledgements

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